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THE АРБУС ORGANIC COOLED AND MODERATED NUCLEAR POWER STATION

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The concept of utilization of small-sized nuclear power plants appeared in connection with the necessity of supplying electric power to the USSR remote difficult-to-reach areas, where the construction of conventional electric plants was not justified from the economic view point mainly due to high costs of fuel transport or its output on the spot. Technical and economic calculations show that for a number of such areas small-sized nuclear engineering may be advantageous even today. As it is known, cost of electric nuclear power is characterized by a relatively high capital cost, notably for small nuclear plants.

Reduction in capital cost may be achieved by using organic coolants, which allow to utilize cheap structural materials, serial equipment and instruments, and due to the primary circuit light biological shield or even absence of it.

But up to date a wide use of organic coolants in nuclear power engineering is restricted due to several undesirable effects connected with radiolytic processes in organic compounds. First of all, these are: build-up of high boilers (B.K) resulted from radiation-induced polymerization which finally might give rise to formation of insoluble compounds deposited as films on fuel element surfaces and to deterioration of coolant thermal and physical

properties. As the operating experience with the OMRE reactor in the USA showed, the most simple system of coolant purification consisting in distillation and rectification although makes it possible to maintain high boilers concentration at a given level, but it does not guarantee against deposits formation at the fuel element surface. In addition, using this purification method, it is necessary to add fresh coolant make-up and dispose high boilers released from the circuit. This fact considerably limits the number of organic fluids which can be used due to high requirements for their radiation stability.

In this connection, in solving the problem of using organic coolants in the nuclear power plant every effort has been made to find the possibility of regeneration of radiolysis high boilers without their removal from the circuit. This makes it possible to use a number of standard materials at low cost, and with comparatively low thermal and radiation stability. As a result, a regeneration system was developed based on catalytic hydrocracking. As preliminary loop tests showed, the parameters having been chosen correctly, this process ensured hydrogenation of unsaturated products of radiation dehydrogenation and selective destruction of radiolysis high boilers. This purification method enabled hydrostabilized gas oil obtained on the basis of direct distillated gas oil fraction of naphtene - aromatic base petroleum to be used as coolant for the first nuclear power plant. Alongside with the well-known advantages of organic coolants there are some more:

1. Low freezing point ($-40^{\circ}C$, $-70^{\circ}C$), thus, the circuit warming-up is not required.
2. Low cost. Gas oil characteristics are given in Table II.

The first nuclear power station of the АРБУС type (Arctic modular reactor plant) has been built at the Nuclear Reactor Research Institute (Melekess, Ylyanovsk district). The АРБУС main parameters are given in Table I.

The nuclear power plant reactor with organic coolant was put into pilot operation on June 23, 1963, after thermal and physical tests the plant went into operation on August 11, 1963.

507

Table I.

The АРБУС Main Parameters

Reactor output	5000 kw
Turbogenerator output	750 kw
Pressure in the primary circuit pressurizer	6 atm
Coolant temperature:	
at reactor inlet	230°C
at reactor outlet	243°C
Coolant flow rate of the primary circuit	600 t/hr
Saturated steam temperature in steam Generator	223°C

Table II.

Hydrostabilized gas oil characteristics

Specific weight at 20°C	0.8558 g/c.c
Iodine number, not greater than 1	
Sulfurizing total	30% (by weight)
Boiling initiation	212°C
Boiling termination	300°C
Carbon content	86.89%
Hydrogen content	1.3.11%
H:C ratio	1.8
Sodium content	2.10^{-5}% (by weight)
Sulfur content	3.10^{-3}% (by weight)
Vapour pressure at 350°C	4.85 atm
Chemical compound:	
paraffin	30.12%
aromatic	30.03%
naphtene	39.85%

Nuclear Power Station General Diagram

The plant design has been chosen to be of two circuits (Fig.1).

The coolant is circulated in the primary circuit by two

307

electric pumps over two parallel circulation passes. Each pump capacity is 430 cm^3/hr at the head of 43 m liquid gauge. Electric motor power is 50 kw. The coolant is fed from the reactor to the steam generators with free surface evaporation, their advantages are as follows: simplicity, reliability and less severe requirements for the feed water. The heat is transferred to the second circuit water in the generators by the coolant, then the coolant comes to pressurizers, which serve degassers as well. Gas is removed from the coolant surface and in special degassing devices, to which 10% of the coolant total flow rate is fed. Coarse gauze filters are also installed in the pressurizer. The coolant is passed from the pressurizers by circulation pumps and it is returned to the reactor.

In the primary circuit pressure is maintained due to gases which are emanated during coolant radiolysis and at the nuclear power plant start-up it is rendered by nitrogen.

Excess gas is rejected to the atmosphere by the pressure regulator.

In the reactor at the initial period residual heat is removed by two turbine pumps in case of de-energizing the primary circuit circulation pumps at the expense of steam accumulated in steam generators, this steam operates turbine pumps for 90 min. and coolant flow rate is 96 t/hr. Then the heat is removed by natural circulation.

The primary circuit coolant is purified by metal ceramic filters installed in bypasses of the circulation pumps. These filters hold suspended particles of greater than 1.5^{-3} mu in size ans they do not let the iron concentration in the coolant be more than 0.3 mg/l. The flow rate through these filters is about 10% of the coolant total flow rate.

The primary circuit filling-up and its making-up are obtained by a pump from a 20 m^3 dump tank. The coolant is passed to dump or drain tank depending on its contamination. Gas oil low-boilers fractions (boiling point up to 120°) forming during the coolant decomposition are condensated in the receiver, then they are periodically drained.

The coolant for regeneration is taken from the primary circuit line and regenerated gas oil is passed to the dump tank.

307

The scheme and principal features of regeneration system are described below.

The second circuit is a part of a conventional condensation steam turbine power plant. In case of an abrupt drop of turbogenerator loading a throttling-welting device is provided in the circuit for direct dumping the excess steam into the condencer. The latter is water cooled. Fig.3.

Nuclear Power Station Layout and its Equipment

The АРБУС plant consists of separate fully mounted factory-assisted and tested units. It comprises 19 units each weighing not greater than 20 tons. The plant total weight together with the reactor shield is 365 tons. The unit weights and size make it possible to transport them to the building site by water or by land. The plant may be mounted on-site in two or three months.

The АРБУС occupies a 12.36 x 28.5 m building and 6.36 m high. An electrolizer and drained devices are located outside the building.

The equipment layout in the buiding is shown in Fig.2.

At the plant start-up the electric equipment is supplied from a 135 kw Diesel-generator.

The primary circuit warming-up and its emergency cooling are accomplished under natural circulation conditions owing to different levels of the reactor and steam generator layout.

The plant is equipped with a container, guider and special tools for reactor refuelling and spent-fuel assembly storage, control and safety system thimbles with rods and manual regulators. The reactor is refuelled with a 12 tons special bridge-crane.

The total personnel is 17.

The equipment, fittings and pipes of the primary circuit are made of carbon steel.

Serial oil pumps and standard oil equipment with increased requirements for the quality of inner surface clean-up are used.

Non-standard equipment is made of "steel 20" structural steel, the casings and bottom dimentions of the reactor, steam generators

307

and pressurizers are unified. Pipes were argon-arc welded in the mixture with carbon dioxide.

The estimation of primary circuit coolant activity showed that it should be not greater than $1.5 \cdot 10^{-4}$ curie/l maximum considering possible fission product release in case of fuel element burst defined at artificial damage of a fuel element can during loop tests. This made it possible not to use the primary circuit shield, except only the reactor shield which may be built from conventional shielding materials (concrete, graphite, polyethilene and iron).

Taking into consideration the plant equipment layout and its operating conditions, the dose rate was estimated to be 0.5 μrem/sec in the serviced rooms and in partially serviced rooms to be 1.7 rem/day, this meets personnel radiation safety requirements.

During test operation at reactor 100% power the dose rate of the pressurizer was 40 μrem/sec, and that for pipes was 3 to 4 μrem/sec. Activity of gases emanated from the coolant radiolytic decomposition was 10^{-12} curie/l. The total gas activity of the plant was about $7.2 \cdot 10^{-8}$ curie/day.

Reactor

The reactor is a welded cylinder, 4365 mm high, 1340 mm in diameter, 20 mm wall thick, at the upper end of which there is a flange with supporting legs and 8 nozzles 150 mm in diameter for the coolant inlet (four, upper) and outlet (four, lower). To reduce the vessel irradiation lateral and lower thermal shields are provided.

There is an inner vessel in the reactor which forms the coolant flow and at the same time serves as the core supporting structure. Uniform distribution before the core is achieved with the help of two perforated plates.

Uranium-aluminium alloy UAl_4+Al has been used as a fuel which gave a minimum fission product release into the circuit in case of fuel element can burst. Total loading of uranium-235 enriched to 36% is 22.5 kg.

307

Maximal design temperature of the fuel element core is 336°C, and that of the can being 335°C.

The physical design of the АРБУС reactor core was based on the results of preliminary critical experiments on the ВВР-М reactor fuel elements described in Paper No.2185 at the Second Conference in Geneva. These elements were chosen as they were similar in geometry and in uranium-235 specific loading.

At the АРБУС reactor start-up the following parameters were determined: moderator critical level for the completely assembled core, control rod number required for total reactivity excess compensation, neutron flux distribution, and rod calibration in the hot "clean" system. The start-up results showed that the calculation method gave the accuracy required when measuring the core physical characteristics. Rather good agreement of design and experimental data was observed when defining critical height H_{cr} for "clean" zone at room temperature (H_{cr}^{exp} = 314 mm; H_{cr}^{des} = 320 mm) and control rod position (Fig.6) in critical cold and hot clean system. Neutron flux distributions experimentally measured over the core radius and height confirmed the design values of non-uniformity coefficients used in heat engineering calculations. (hot spot coefficients).

When the temperature effect and coefficient of reactivity were determined the system was warmed-up from the external heat source from 20°C to 200°C. The results obtained were extrapolated to the coolant operating temperature (245°C) and they showed that the value of temperature effect experimentally obtained in the range 20 - 245°C was about $\Delta K_{eff} = 1.4 \cdot 10^{-2}$ above the design one which is equal to $6.1 \cdot 10^{-2}$. The temperature reactivity coefficient is negative in the whole temperature range and equal to $-4.3 \cdot 10^{-4}$ 1/°C under operating conditions.

Taking into consideration the corrections made at the start-up and power operation the effective multiplication factor for various reactor conditions is as follows: at the core life beginning at t = 20°C K_{eff} is 1.264, for hot clean reactor K_{eff} is 1.189, for hot poisoned reactor K_{eff} is 1.148.

At reactor full power operation the core life is about

307

2 years. The reactor control system includes cylindrical rods, moving in the reactor core.

Two boron steel rods are designed for automatic control (rods AP).

30 boron steel rods compensate the temperature and poisoning effects (rods KC). These rods account for about 12% reactivity.

In case of accidental conditions of the first kinds (that is coolant flow rate failure in the primary circuit or increase in the runaway rate) all these rods fall into the core.

Two rods KC connected in pairs are of safety system (A3) of the second kind. The safety system signals include the signals of design power-level overshoot, power supply failure and other technological signals.

37 boron carbide rods are designed for compensating the burn-up effect. These are used as two position rods and account for about 18% reactivity.

Reactor control, regulation and power safetyare provided by measuring the neutron flux with compensated ionization chambers. The latter are placed in special hermetically sealed hangers located in the space between the chimney and reactor wessel.

The hangers occupy 12 channels, 5 channels with lead shrouds are designed for start-up hangers. Magnetic amplifiers are chiefly used in control and safety system which ensure stable operation at low remperatures and are easily transported over long distances.

Reactor is controlled by one automatic regulator, the second one being stand-by. The design power level stability is kept within ±1%.

The reactor automatic start-up is provided by an instrument which brings the reactor from $(10^{-4} - 10^{-5})$%N nominal to (1-10)%N nominal with preset period. Within this range this automatic start-up instrument ensures safety when the power rate increases.

Dynamic Characteristics Studies and Plant Regulation

The plant dynamic characteristics have been studied on an electronic model and then directly on the АРБУС plant.

As a result of these investigations it was found that all the processes are relatively slow both under operating and emergency conditions, this being a special feature of the plant.

All these transients are slow, this is attributed to relatively large amount of the coolant in the primary circuit and boiling water in the steam generators and is favourable from the view point of thermal conditions of the fuel elements and the primary circuit structures.

The temperature self-regulation research of the plant has shown that its sufficient stability ensures its normal operation under design conditions without an automatic regulator of the reactor neutronic power. The maximum permissible sudden increase in reactivity of the system at an acceptable deviation of technological parameters, being about + 0.1 ß and - 0.3 ß.

Under self-regulation conditions the plant automatic transition from one power level to another is possible with the automatic regulator off, when the coolant temperature level and steam pressure being changed in the proper way. (Fig.7).

Investigations of the coolant flowrate perturbations showed that the flowrate variations with an amplitude up to 10% and frequency from 0.01 cps and up proved to be permissible. No changes in parameters were observed at a frequency greater than 0.3 cps.

During the plant operation under nominal conditions an instantaneous rejection of 260 kw leads to the steam pressure rise in the second circuit about by 3 atm; at subsequent loading of 260 kw the system parameters acquire again their original values.

As a result of the emergency shut-down cooling of the primary circuit when the circulation pumps fail it was found that the temperature of the fuel element surface does not exceed the permissible value if the emergency turbopumps begin to operate not later than in 3 seconds. The experience gained directly at the plant showed this time being equal to 0.2 sec.

The normal operation time of the turbogenerator for its own purposes after the scram shut-down is equal to 18 sec.

The results of studies on an electronic simulator were confirmed during the plant testing. Change in plant parameters with

307

increase in electric load is shown in Fig.4.

Conservation and the primary circuit purification

The power plant, where the primary circuit is made of carbon steels and without a biological shield, should meet the main requirement, that is organic coolant purity. For this purpose the equipment and piping of the primary circuit were subjected to thorough chemical or mechanical treatment to remove contamination and corrosion products with subsequent conservation with a volatile inhibitor (50% water solution of monoethanolamine) and they were sealed for transportation and mounting.

After mounting and dried air pressing the circuit was filled with a petroleum fuel "ДА" type (similar in composition to gas oil) containing 1 mg of iron per liter, the circuit has been subjected to hot washing. When washing the temperature was kept close to operating one. To achieve maximum effect the circuit was washed in three stages. After each stage the fuel was poured out and replaced with a new portion. The washing process was controlled according to iron content in the fuel. The conservation and purification technology described made it possible to start the plant with 0.2 - 0.3 mg of iron per liter.

Coolant Regeneration

To remove polymers and unsaturated compounds from the АРБУС primary circuit a special system of organic coolant regeneration was developed by a continuous partial removing it to a hydrogenated reactor. In this reactor with alumocobalto-molybdenum catalyst unsaturated unstable compounds are hydrogenated and polymers are destructed under hydrogen pressure, a total of 80 per cent of compounds being formed, their physical and chemical properties are similar to original ones. The rest of 20 per cent compounds are light products and coke. During such a regenerating process the coolant is additionally purified from metal and sulfur traces. It should be noted that in this case the hydrocracking process is more simple due to character of linking in chemical

radiation polymers. The regeneration conditions are chosen in such a way as not to allow aromatic compounds to be hydrogenated.

The results of investigations showed that when applying hydrogenated regeneration to coolants prepared from gas oil fractions of petroleum the optimal parameters were as follows:

Hydrogen pressure	40-60 atm
Temperature in reactor	350-380°C
Volumetric velocity	0.5 hr^{-1}
Raw material-hydrogen molar ratio	1:5 to 1:10

The general arrangement of the regeneration system is shown in Fig.1. The coolant comes from the primary circuit (200-250 liter/hour) to the regeneration system gas oil pump. Then the gas oil at a pressure of 45-60 atm is mixed with an inflow of circulating hydrogen. The latter is obtained by water electrolysis in an electrolyzer from which it is transported to the system by a displacement compressor of the regeneration system. The gas oil and hydrogen mixture is heated in the regenerative heat exchanger, and then it is heated up to the working temperature in an electric furnace. After that the gas oil and hydrogen mixture is fed to the reactor filled with catalyst. The hydrogen and regenerated gas oil mixture coming from the reactor transfers its heat in the heat exchanger, and is finally cooled down to 30-50°C in the cooler. Then the mixture is separated in a gas separator from which the gas oil comes through cermet and felt filters to the primary circuit feed tanks, and hydrogen flows to the circulating compressor. Owing to formation of destruction gas products (methane), small amounts of the circulating gas are continuously rejected to an exhaust stack. Hydrogen total flowrate is found to be 0.45 kg/hr, hydrogen in the amount of 0.36 kg/hr directly takes part in the reaction.

Radiation-induced Chemical Changes of Coolant

In general good agreement was obtained between the radiation-induced chemical characteristics of the hydrogenated gas oil and the results of preliminary experiments and loop tests carried

307

out on АРБУС. Fig.7 shows the temperature relation of viscosity for original and irradiated gas oil of the АРБУС primary circuit containing 9.03% high boiling products of radiolysis (BK). Changes in density, viscosity, iodine number and content of radiolysis high-boiling products with growth of integral dose are shown in fig.6 and 7 during operation without regenerating unit. Absorption curve of radiation energy per 1 g gas oil is shown in Fig.7.

On the basis of the results obtained an initial value of high boilers formation has been calculated, that is, about 2 molecules/100 ev. In prolonged operation this value reduces to about 0.5 molecules/100 ev.

The composition of gas formed as a result of radiolysis has been tabulated (Table III). Coolant flowrate to fill up the losses due to radiolytic decomposition at 100% power operation amounts to 20-30t/year.

Table III. Gas Composition Formed During radiolysis

Components	Content in %	
	weight	volume
Hydrogen	26.670	83.077
Methane	24.191	9.415
Ethane-ethylene	13.634	2.829
Propane	11.079	1.566
Propylene	9.060	1.343
N -Butane	5.496	0.590
Acetylene	0.548	0.132
Butane	2.081	0.224
Allene	0.386	0.061
ß, i + d - Butylenes	6.219	0.692
ß - Butylene + Divinyl	0.636	0.071

Conclusion

Construction and pilot operation of the АРБУС power plant showed the possibility of building nuclear power plants with organic moderated reactor in remotely sited areas of the USSR.

The operating experience confirmed the correctness of calculations and principal considerations underlying the design, the possibility of making the primary circuit equipment and pipes of carbon steel without shielding and the possibility of using serial petroleum equipment and standard fittings considering the requirements for a power plant. This nuclear power plant is rather stable, simple and reliable in operation under various conditions.

There is a possibility of further improving technical-economic characteristics of the plant of this type by improving parameters (use more heat resistant regenerated coolant) and modifying the plant on the basis of operating experience accumulated.

307

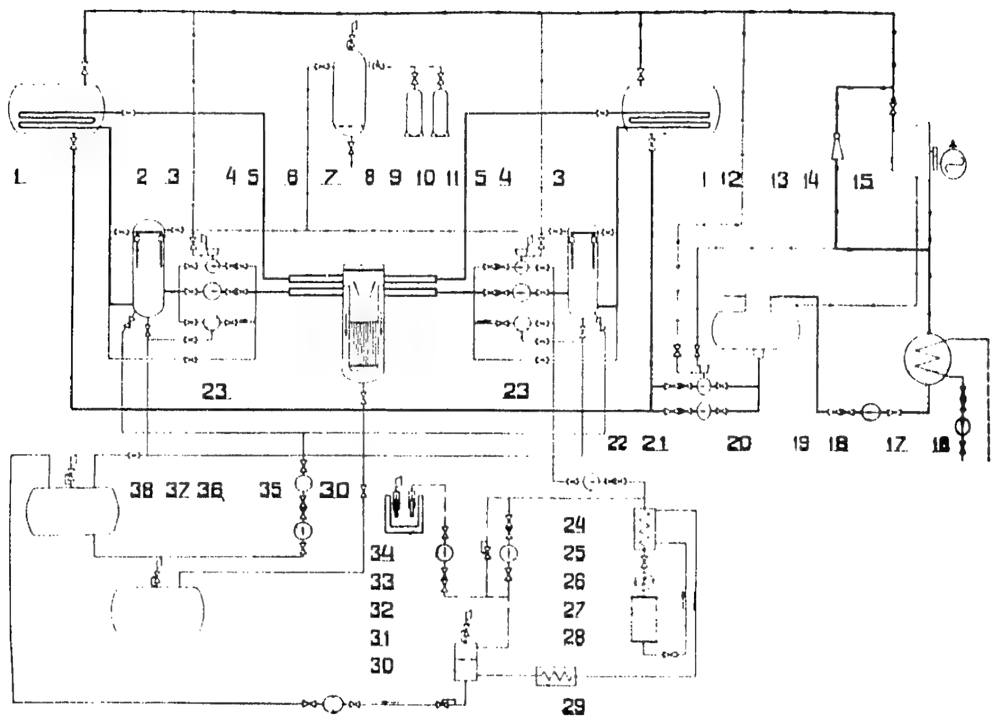

Fig. 1. The АРБУС General Diagram.
1 - steam generator, 2 - primary circuit main piping, 3 - pressurizer, 4 - emergency turbine pump, 5 - main circulation pump, 6 - gas piping, 7 - reactor, 8 - removal of gas oil light fractions, 9 - receiver, 10 - control valve, 11 - nitrogen cylinder, 12 - water supply from chemical water treatment system, 13 - steam piping, 14 - throttle-wetting device, 15 - turbine with reducer and generator, 16 - circulation pump, 17 - condenser, 18 - condenser pump, 19 - deaerator, 20 - feed electric pump, 21 - feed turbine pump, 22 - second circuit piping, 23 - metal ceramic filter, 24 - regeneration system gas oil pump, 25 - regenerative heat exchanger, 26 - circulation pump, 27 - electric furnace, 28 - reactor with catalyst, 29 - cooler, 30 - gause filter, 31 - gas separator, 32 - system regeneration gas oil compressor, 33 - hydrogen piping, 34 - electrolyzer, 35 - feed pump, 36 - auxiliary gas oil piping, 37 - drain tank, 38 - dump tank.

307

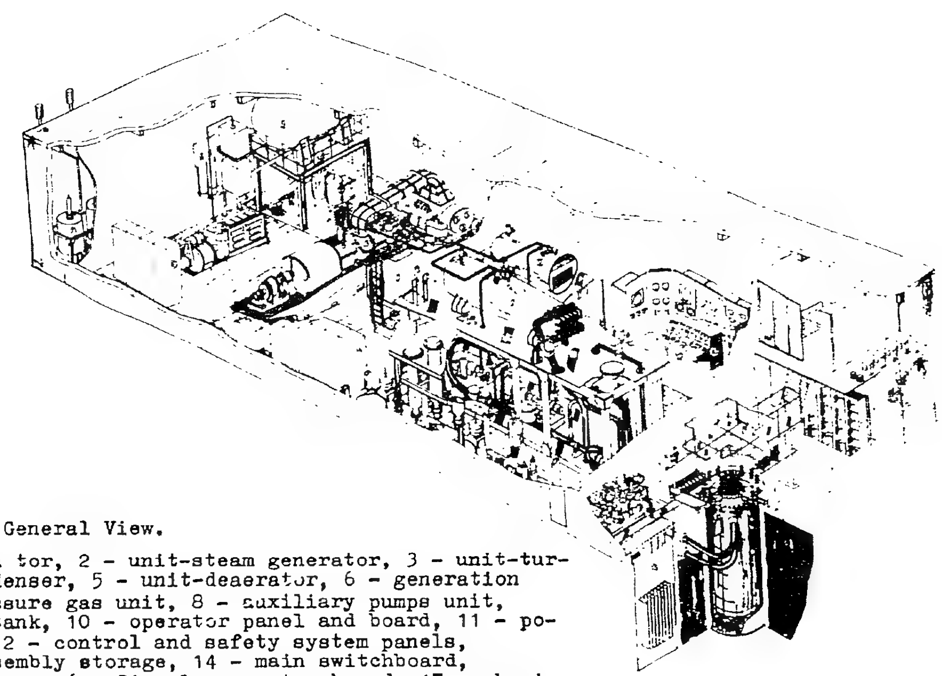

Fig.2. The АРБУС General View.

1 - unit-rea tor, 2 - unit-steam generator, 3 - unit-turbine, 4 - unit-condenser, 5 - unit-deaerator, 6 - generation unit, 7 - high pressure gas unit, 8 - auxiliary pumps unit, 9 - water storage tank, 10 - operator panel and board, 11 - power supply panel, 12 - control and safety system panels, 13 - spent-fuel assembly storage, 14 - main switchboard, 15 - Diesel-generator, 16 - Diesel-generator board, 17 - chemical water trearment unit.

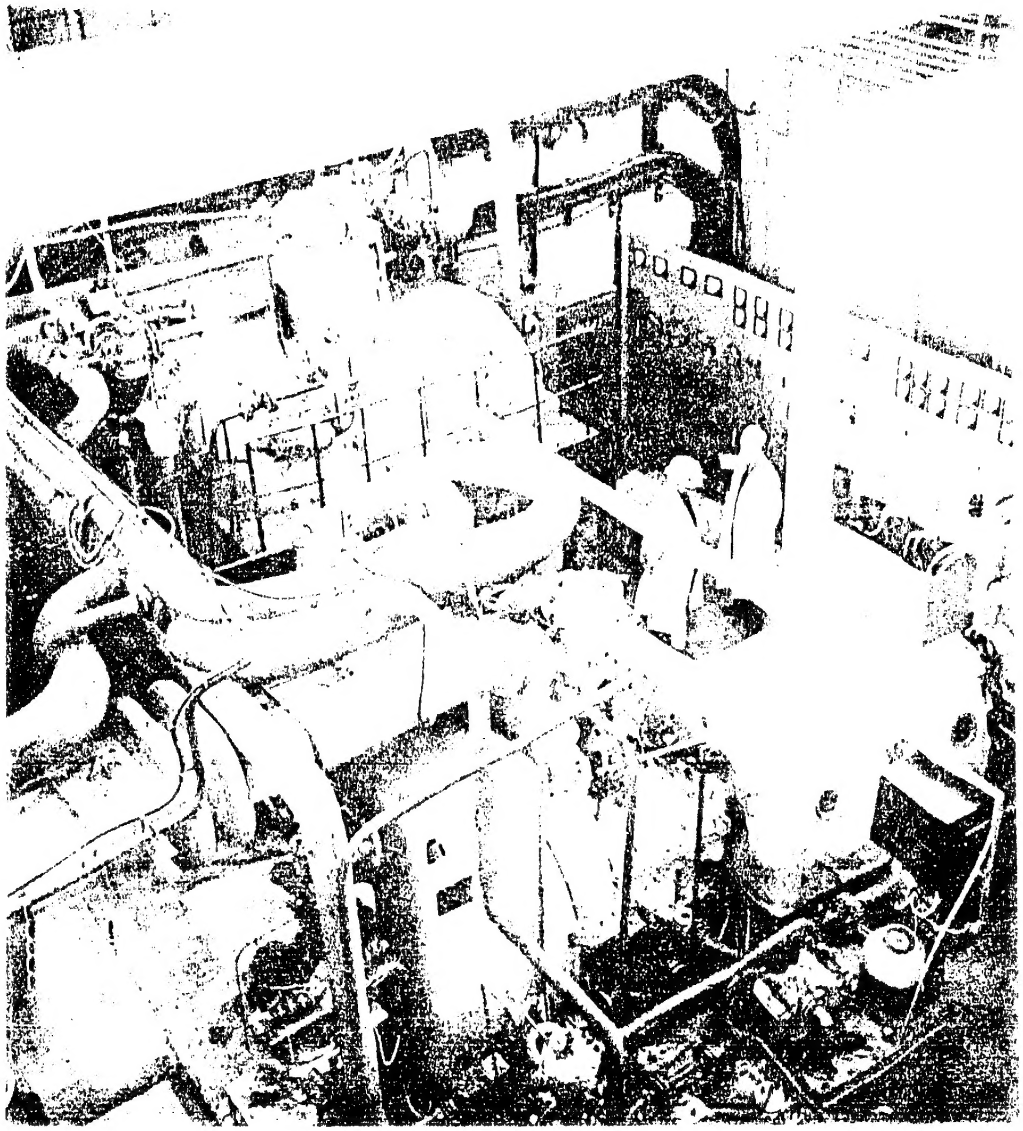

Fig.3. Plant power equipment. Turbine generator.

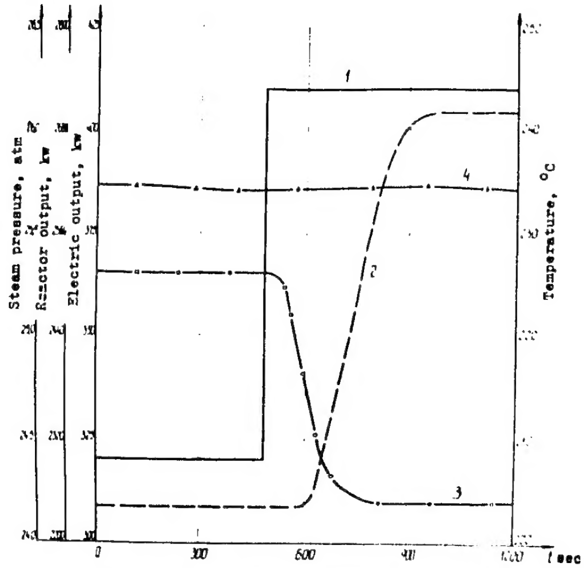

Fig.4. Change in the plant parameters when electric load increases (tests during the plant operation).
1 - electrical output, 2 - reactor power, 3 - steam pressure, 4 - coolant temperature at the reactor outlet.

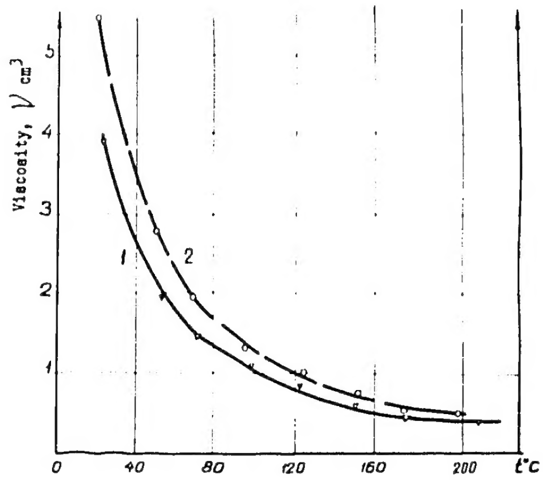

Fig.5. Gas oil viscosity vs temperature.
1 - original gas oil, 2 - gas oil containing 9.03% high boilers.

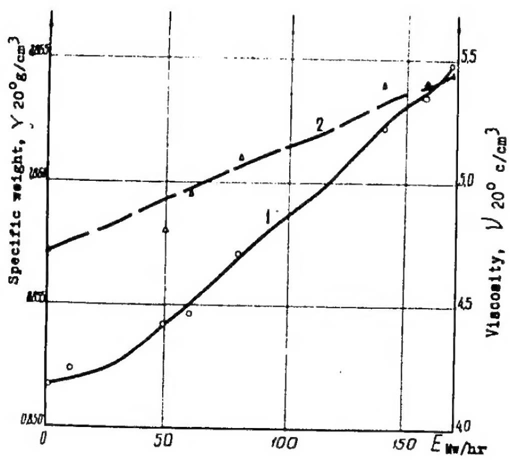

Fig.6. Change in gas oil viscosity and specific weight vs integral dose rate.
1 - viscosity, 2 - specific weight.

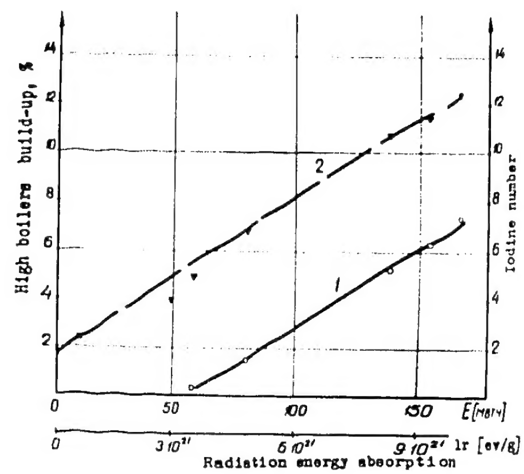

Fig.7. High boilers build-up and change in iodine number vs integral dose rate.
1- high boilers concentration, 2 - iodine number.

307

Figures to the Paper "The АРБУС Organic Cooled and Moderated Nuclear Power Station"

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1 - unit-reactor, 2 - unit-steam generator, 3 - unit-turbine, 4 - unit-condenser, 5 - unit-deaerator, 6 - regeneration unit unit, 7 - high pressure gas unit, 8 - auxiliary pumps unit, 9 - water storage tank, 10 - operator panel and board, 11 - power supply panel, 12 - control and safety system panels, 13 - spent--fuel assembly storage, 14 - main switchboard, 15 - Diesel-generator, 16 - Diesel-generator board, 17 - chemical water treatment unit.

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Fig. 5. Gas oil viscosity vs temperature.

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307

Fig. 6. Change in gas oil viscosity and specific weight vs integral dose rate.

2 - viscosity,

3 - specific weight.

Fig. 7. High boilers build-up and change in iodine number vs integral dose rate.

1 - high boilers concentration,

2 - iodine number.

307